EMISSIONS OF NO_X FROM BALTIC SHIPPING AND FIRST ESTIMATES OF THEIR EFFECTS ON AIR QUALITY AND EUTROPHICATION OF THE BALTIC SEA

Authors:

Tapani Stipa	Finnish Institute of Marine Research
Jukka-Pekka Jalkanen, Marke Hongisto	Finnish Meteorological Institute
Juha Kalli	University of Turku
Anders Brink	Åbo Akademi University

ISBN: 978-951-53-3028-4

Date of preparation: 2007-12-27

This report is a copyrighted contribution to the ShipNOEm project, funded by Finnish Ministry of Transport and Communication and the Finnish Maritime Administration, and to the Interreg IIIa projects ShipNODep. The projects are part of the ShipNODeff programme (www.shipnodeff.org).

Executive Summary

For the first time an estimate of the atmospheric emissions from shipping has been created from observed shipping information in the Baltic Sea. The estimate is based on information from the Automatic Identification System collected by the Baltic Sea countries and is verified against information on fuel consumption obtained from shipping companies and *in situ* measurements of air quality near fairways. The estimate of the total NOx emissions in the Baltic (370 kton NOx/year) is likely to be an underestimate at this point; it is higher than other present estimates though.

The Baltic Sea traffic is intense and grows by around 5% per year. The total number of vessels sailing in the Baltic is 3,500-5,000 each month, depending on the season. The largest ship categories are general cargo carriers and oil/chemical tankers. However passenger ships have the highest fuel consumption and second highest NOx production.

In terms of NOx production, the largest contribution is from ships built after the year 2000 (32%) with ships built between 1990 and 2000 contributing by approximately an equivalent amount (28%). Vessels with size above 8000 GRT (i.e. ships with mostly 2-stroke engines) contribute more than 55% of the emissions.

The NOx emissions from shipping in Finnish waters alone are higher than emissions from Finnish land traffic. On the Baltic Sea scale, the emissions from shipping estimated in this report are comparable to the combined land-based NOx emissions from Denmark and Sweden.

The emissions, if they were directly deposited to the sea at the source, would contribute significantly to the dissolved inorganic nitrogen concentrations in the Baltic Sea, and therefore to the eutrophication in the Baltic. A month's worth of ship emissions would increase the nitrogen level in the sea within 10 km of the shipping lane by about 5-20% of the winter nitrogen concentration.

When dispersed and deposited in the atmosphere by real atmospheric chemistry, the effect of ship emissions becomes diffuse and extends over large areas of the Baltic Sea. However, the most recent calculations of EMEP[*] identify Baltic shipping as the largest contributor to atmospheric nitrogen oxide deposition to the Baltic Sea with a share of 16%; the present study shows the contribution to reach up to 50% in some areas and seasons. The atmospheric deposition of nitrogen in total contributes to about 25-30% of nitrogen input to the Baltic Sea, and is therefore a significant contributor to its eutrophication.

[*] Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air pollutants in Europe

Contents

Figures

1. Introduction

Marine environment protection in Europe (and already earlier in North America) is shifting from defining emission reductions towards defining a target status of sea areas. This is a major shift in thinking, which requires the research community to address the full pathway from the emissions to the effects, and in order to give advice how to change the status, the pathway back from the deviation from the target status to the most efficient means to reduce the adverse environmental effects of human actions.

Eutrophication, the main problem in the Baltic Sea ecosystem, is mainly regulated by two main nutrients, phosphorus and nitrogen. Both of them can act as a limiting factor, depending on circumstances. In open sea areas, nitrogen has in many direct and indirect studies been found to be the nutrient regulating primary production and hence, the overall eutrophication.

Shipping is an important source of nitrogen through its exhaust emissions, and its share compared to other sources is rapidly increasing. This is mostly due to increasing ship traffic volumes in the Baltic Sea area.

Most inventories used to estimate the global role of nitrogen for the Baltic ecosystem are based on out-of-date emission inventories from early 1990's. These inventories are still used in the international air pollution reduction negotiations. More recent assessments are based on port statistics and aggregate the emissions for large areas.

NOx from ships is generated mainly from the nitrogen contained in the air that enters the engine during the combustion process, while the nitrogen carried in with the fuel is irrelevant. The amount of NOx emitted from every ship is the result between the NOx that have been formed in the engine and those that have been destroyed in the engine itself and along the exhaust duct.

The extent of NOx formation and destruction strictly correlates with the ship operation and the composition of the fuel used in it. The operation of the ship reflects on the load and speed at which the engine is operated, which in turn affects the temperatures in the engine, and ultimately controls the amount of NOx emitted. Therefore, detailed information about the ship operation is beneficial for the emission estimation.

The dynamic nature of the Baltic Sea ecosystem causes one dose of atmospheric deposition to have different effects, depending on the exact deposition compound, the time of the year, the nutritional status of the year, and most likely to some extent, the prevailing plankton community in the sea. Therefore, time-dependent estimates of the state of the sea as well as the NOx emissions and their deposition are needed to evaluate the effects.

The goal of this study has been to use the Automatic Identification System (AIS) information recorded by the Baltic Sea States (Denmark, Estonia, Finland, Germany, Lithuania, Latvia, Poland, the Russian Federation, Sweden) in order to estimate NOx emissions from the shipping in the Baltic, that could be widely accepted, and to use that emission to produce first estimates of the deposition of ship-borne nitrogen as well as its effects. In the following section the results of the AIS database analysis are introduced. The emissions derived from the dataset are analyzed in **Section 3** and compared to other emission sources in **Section 4**. The atmospheric behavior, deposition to the sea as well as effects in the sea are analyzed in **Section 5**, and the effect of measures to reduce the NOx emissions as planned by IMO are presented in **Section 6**.

2. Shipping pattern in the Baltic Sea

A one year period of AIS data from March 1st 2006 – February 28th 2007 was obtained from the AIS database of the Baltic Marine Environment Protection Commission (HELCOM) maintained by Denmark. There are 8510 unique and reasonable MMSI codes in the dataset. These are the ones that were transmitted more than once during a year's time and are more likely to tell the number of ships than the total number of unique MMSI numbers (10859).

On a monthly level the distribution of different ship types are given in **Table 1**. This table shows the distribution of ship types in March 2006 in the Baltic Sea area.

Table 1: Number of ships and their proportion in total number of ships in March 2006 in the Baltic Sea region

Ship type	**Number of ships**	**%, ships**
Passenger	201	5.8
RoRo Cargo	121	3.5
Container Cargo	103	3.0
Oil/Chemical Tanker	539	15.5
General Cargo	1152	33.1
Vehicle Carrier	68	2.0
Refrigerated Cargo	115	3.3
Bulk Cargo	247	7.1
Icebreaker	29	0.8
Barge	4	0.1
Other	89	2.6
Tug, Dredger, Pilot	812*	23.3
Total	3480	100

* This is the smallest possible emission category. The class holds all the vessels that do not fall into any other category, including unidentified vessels.

Roughly every fourth ship cannot be identified by using an IMO number. The vessel may not have a valid IMO registry number, its static AIS message was not received during the trial period, IMO number is invalid or it is missing from AIS transmission. MMSI number was used as a secondary means of identification. Still, more than every fifth ship cannot be identified reliably. **For this reason, it is very likely that NOx emissions reported later on in this document are underestimated for the Baltic Sea.** Although Table 1 shows the situation from March 2006, the percentages of ships change only slightly when this analysis is repeated over the one-year period.

For March 2006, the vessel size and engine distribution is shown in **Table 2**.

Table 2: The size classes of the ships sailing in the Baltic Sea region in March 2006

Vessel size, GRT	**Number of vessels**	**2-stroke**	**4-stroke**
GRT < 300[†]	76	5	71
300 < GRT < 1000	293	24	269
999 < GRT < 2500	661	13	648
2499 < GRT < 4500	566	18	548
4499 < GRT < 8000	328	224	104
7999 < GRT < 12000	209	185	24
11999 < GRT < 21000	279	243	36
20999 < GRT < 50000	313	267	46
GRT >= 50000	108	100	0
Unknown	647		
Total	3480		

The turnover from four-stroke engines to two-stroke engines appears to happen when GRT of a vessel is between 5000 and 8000. These numbers are based on real engine data obtained from Lloyds Register. If the data is unavailable four-stroke engine is assumed during the exhaust estimation if the vessel is a passenger ship or its GRT is less than 5000.
The age distribution of the ships is given in **Table 3**.

Table 3: The age of the ships sailing in the Baltic Sea region in March 2006. DOB = Date of build

Build year	**Number of vessels**
2000-	654
1989 < DOB < 2000	753
1979 < DOB < 1990	745
1969 < DOB < 1980	553
1959 < DOB < 1970	97
DOB ≤ 1960	33
Unknown	645
Total	3480

[†] AIS equipment is mandatory for vessels >300 GRT, however according to Regulation 5, Annex VI to MARPOL 73/78, ships GRT<400 shall not be subject to surveys related to the Annex.

Figure 1 shows the average traffic density in the Baltic Sea. This figure does not make a distinction between large and small vessels. The figure shows the number of ships on each of the grid cells summed over 15 minute periods. This will highlight major ports and heavily trafficked areas.

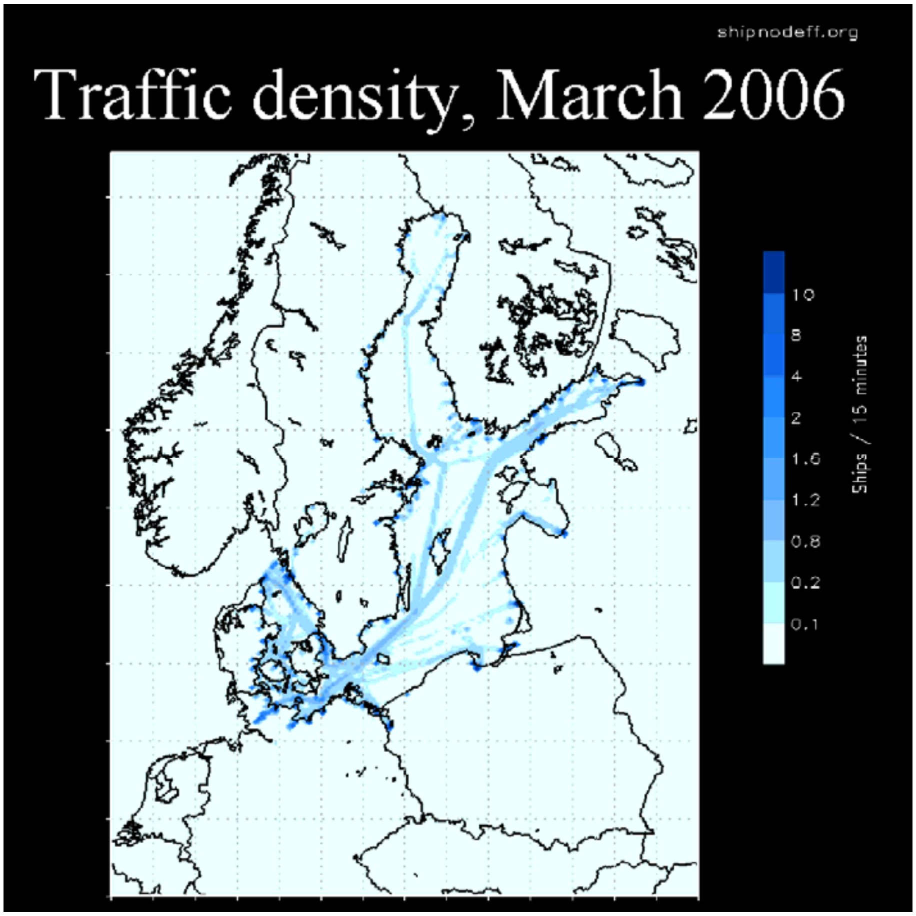

Figure 1: Traffic density plot of the Baltic Sea. The unit of the graph is an average number of ships/15 minute time intervals.

3. Information on estimated NOx emission from the Baltic Sea shipping for one year period based e.g. on AIS data.

3.1. Description of estimation method

The required engine effect is the product of the effect required to move the ship and efficiency of the propulsion system. The required effect to move the ship consists of effect required to overcome the frictional resistance, the residuary resistance and resistance caused by wind, wave and ice. The efficiency of the propulsion system is a function of design but also of the load. To estimate the instantaneous power requirement some basic formulas can be used, e.g. those presented at the International Towing Tank Conference in 1957. These expressions include several ship specific parameters, which cannot be obtained from available ship registers. It is possible to estimate many of these parameters based on the ship type and its dimensions. In practice, however, this leads to a power-velocity relation that shows that the power is proportional to the cube of the velocity. This reduces the problem to that of finding a coefficient that relates the power to the cube of the velocity. This can be done using the information listed in shipping registers. Here, one must take into account that the listed ship cruising speed will typically include a safety margin in engine power. For the power calculations, the instantaneous velocity is obtained from the AIS signal, which is also used to identify the ship.

The AIS data gives no information on the use of auxiliary engines. In the report, the auxiliary engine use is estimated using two ship categories: passenger ships and other ships. For passenger ships an auxiliary engine load of 4000 kW is used regardless of size and operational mode. For other ships it is assumed that 750 kW is used during cruise, 1250 kW during maneuver, and 1000 kW during hoteling. In all cases, an additional restriction has been used, i.e., that the auxiliary engine effect is less than 20% of the main engine. In the emission calculations the operational mode is determined from the ship velocity as provided by the AIS signal.

3.1.1. NO_x base line estimate

Two different families of emission estimates are performed: a baseline estimate with a simple method (described in this section) and supporting emission estimates (not shown) performed with an algorithm that builds on the IMO NOx curve (described in Section 6; the results agreed within a few percentage between the baseline estimate and the IMO Tier I estimate).

In the first calculations, used as a base line estimate, it is assumed that ships larger than 5000 gross tonnage are equipped with low speed diesels, whereas other ships are equipped with medium speed diesels. Also passenger ferries belong to this category independent of their size. If there are a large number of ships equipped with gas turbines, these need to be taken into account separately.

Knowing the instantaneous engine power setting the NO_x production can be obtained. Here it is assumed that slow speed engines produce 17.5 g NO_x/kWh. The NO_x production for medium speed diesels is calculated as either as 12.0 g NO_x/kWh or with the equation

$$4.25 \text{ g } NO_x/\text{kWh} * P^{1.14}/P,$$

whichever is greater. P is the engine power in kW.

3.2. Results from NOx estimation

Analysis of one year HELCOM AIS data covering the Baltic Sea region was made and annual NOx emission arising from marine traffic analyzed. The annual NOx emission from ships is estimated as 370 kilotons. *Figure 2* shows the monthly variations in NOx emissions.

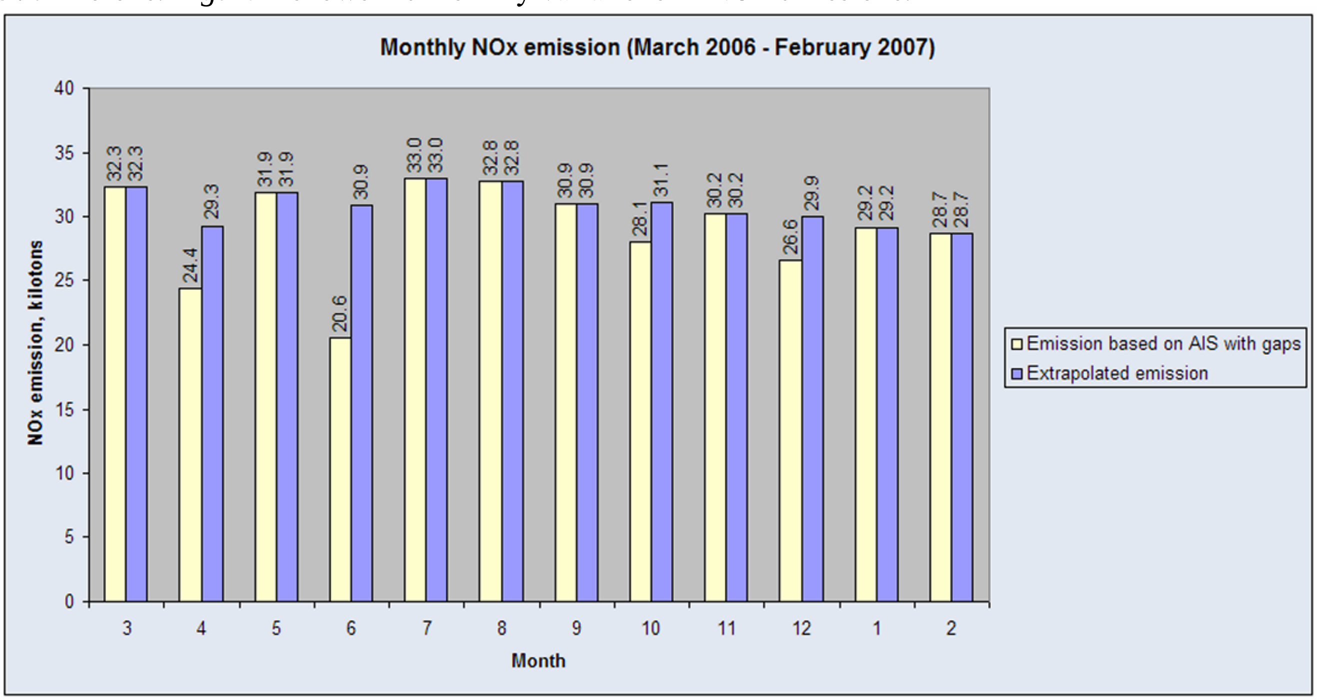

Figure 2: Monthly emissions of NOx from marine traffic in the Baltic Sea

The AIS data itself may not be complete, as was the case with the analysis of March 2006 – February 2007 time period. Gaps up to 6.5 days could be found, and the total number of days missing is 21.5. This can be dealt with at least in two ways 1) reporting the annual NOx emission, but recognizing the fact that the time period is incomplete and leaving the estimate "as it is" or 2) recognizing the incomplete nature of the data and estimating the effects of data gaps to total emission. The former annual NOx emission is 348.4 kt/year and it is shown in **Figure 2** as blue bars. The latter approach produces 370.0 kt/year and is shown in **Figure 2** with yellow bars. The uncertainty caused by data gaps is less than ten percent.

It must be noted that the weather effects like the wind, waves and ice are not yet covered by these estimates. They are part of the dispersion modeling and pollutant transport, but their effect to the ability of a ship to travel through water has not been included in the model yet. The geographical distribution of NOx emissions in March 2006 can be seen in **Figure 3**. Most of this emission is concentrated on the southern part of the Baltic Sea, around the Danish straits and the Kiel Canal where the ship traffic is intense, but significant emissions can also be seen throughout the Gulf of Finland.

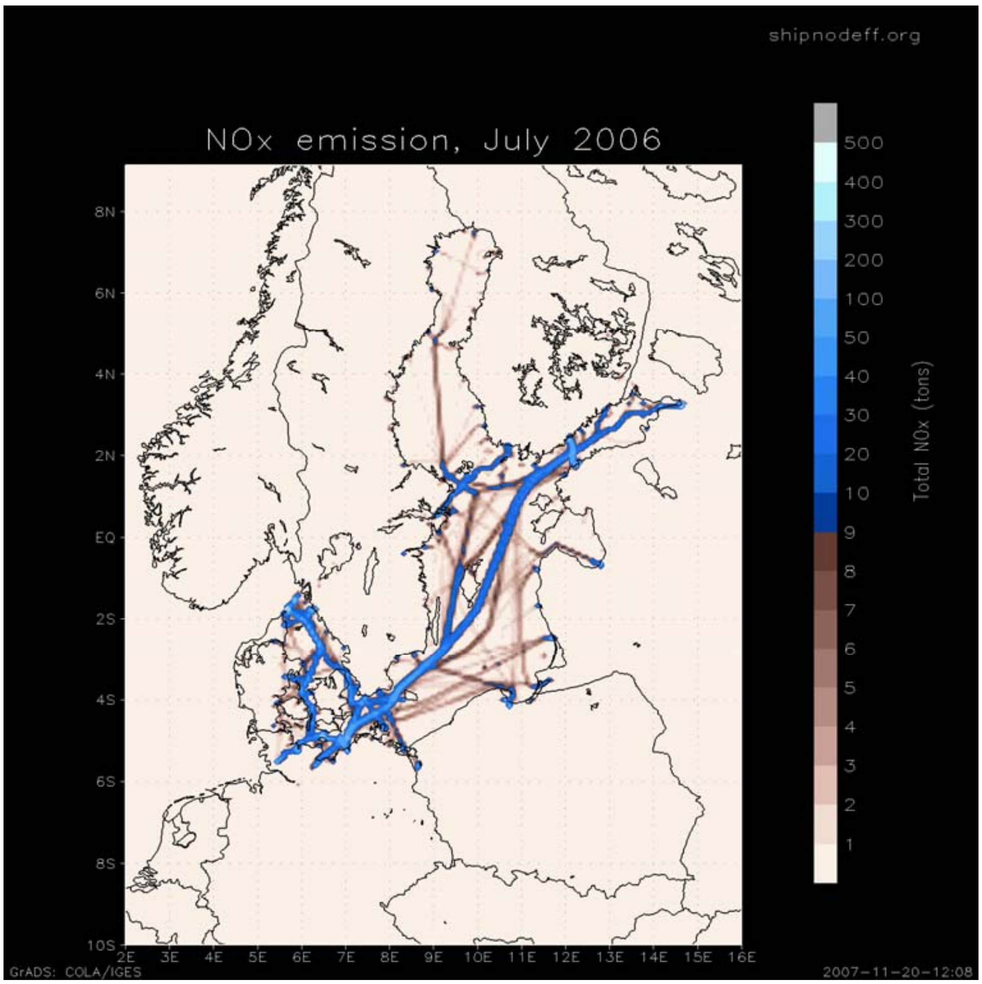

Figure 3: Geographical distribution of NOx emission in July 2006. The unit is tons of NOx / grid cell of 0.08° x 0.08° (roughly ~9 km by 9 km) in one month.

Major ship routes are easily identifiable and peak values for NOx emissions as high as several hundred tons/month can be observed on heavily trafficked areas of the Southern Baltic Sea. The total NOx emission from shipping was ~33 kilotons in July 2006. These emissions arise from various ship types. The type specific emissions are collected in **Table 4**.

Table 4: Emissions by ship type; the total annual emission is 370 kt.

Ship type	Total NOx emitted (kg)	% of ships	% of total NOx emission
Passenger ships	75 958 250	5.9	20.5
RORO Cargo ships	61 014 506	3.1	16.5
Container Cargo ships	22 942 045	2.8	6.2
Oil/Chemical Tankers	61 845 020	14.1	16.7
General Cargo ships	65 440 336	34.4	17.7
Vehicle Carriers	14 412 660	1.5	3.9
Refrigerated Cargo ships	6 097 038	2.4	1.7
Tug, Pilot, Dredger, Unidentified	38 496 654	28.5	10.4
Other ships	3 439 381	2.5	0.9
Bulk Carriers	16 715 195	4.0	4.5
Icebreakers	3 591 398	0.6	1.0
Barges	63 352	0.1	<0.1
Total (kg)	~370 000 000	100 %	100 %

Some uncertainties that affect the accuracy of the NOx emissions shown in this document are listed in **Table 5**.

Table 5: Sources of uncertainty in exhaust calculation: small (<10 %), moderate (<25 %), large (>25 %).

Source	NOx output	Influence
Unidentified ships	Underestimates	Small - Moderate
Data gaps	Underestimates	Small
Estimated fuel consumption	Underestimates	Small – Moderate
Weather	Underestimates	Small – Moderate
Main engine use	Underestimates	Small – Large
Auxiliary engine use	Overestimates	Small

Approximately 20 % of the ships remain unidentified. Even though the AIS system sends out both dynamic and static messages, identification is likely to fail if no static message is received and no connection to national MMSI databases are available. It is understandable that small vessels may not transmit a valid IMO registry number, because they might not have one due to small size of the vessel. **Unidentified vessels are treated as smallest possible sources of emissions: tugboats,** which do not reflect the reality, thereby leading to underestimation of the NOx emission of the vessel.

The first column in Table 5 lists possible sources of uncertainty when making the NOx emission estimates. The second column describes the effect to NOx emission, most of the listed uncertainties lead to underestimated emission values, like the calculated fuel consumption of ships. The fuel consumption produced by the ShipNODeff computer program is a bit lower than what are the actual amounts for main engines. In some ships the difference is ~25 %, but results showing ~50 % underestimation can be found in some cases. The source of this controversy is unknown, because with some ship types predicted fuel consumptions are quite close to reality, while some others show larger deviations. One possible explanation is that a usage pattern of a ship is quite different than what is expected in the computer program. For example, a ship may not travel its route from point A to B as expected, but spends some time waiting in the open sea due to lax schedule. In all the compared cases, the program underestimated the fuel consumption of main engines. In auxiliary engines the effect was opposite: the program restricts auxiliary engine use to a maximum of 20 % of main engine power of any ship. In passenger ships, auxiliary engine use of 4 MW is used regardless the fact that ship may be cruising, remain anchored or undergoing port maneuvers. This value may be slightly overestimated for small passenger ships and too small for large cruise ships. The underestimation of fuel consumption of main engines tends to **underestimate** NOx emissions, while slight overestimation of fuel consumption of auxiliary engines lead to **overestimation** of NOx emissions.

Weather certainly affects the ability of a ship to travel through water. Wind, waves, currents and ice conditions may have a small to moderate effect on predicted engine power usage. Neglecting these effects will show an underestimation of required engine power and fuel consumed and will produce **too low estimates for NOx** emissions.

Combining these effects reveal that the only factor resulting to possible overestimation of NOx emissions and fuel consumption is the ship's auxiliary engine use. **The reported annual NOx emission from marine traffic reported in this paper is more likely to be underestimated than too large.**

Statistics of NOx production by ship type is shown in **Table 6**.

Table 6: Statistics on number of ships listed by type, their fuel consumption and NOx output in March 2006.

Ship type	**Number of ships**	**Total NOx (tons)**	**Fuel consumption (tons)**	**%, ships**	**%, NOx**	**%, Fuel**
Passenger	201	6 031	101 279	5.8	18.7	21.7
RoRo Cargo	121	5 377	71 918	3.5	16.6	15.4
Container Cargo	103	1 746	22 664	3.0	5.4	4.9
Oil/Chemical Tanker	539	6 117	79 337	15.5	18.9	17.0
General Cargo	1152	5 260	78 852	33.1	16.3	16.9
Vehicle Carrier	68	982	12 795	2.0	3.0	2.7
Refrigerated Cargo	115	650	8 940	3.3	2.0	1.9
Bulk Cargo	247	2 149	28 685	7.1	6.7	6.1
Icebreaker	29	1 019	13 691	0.8	3.2	2.9
Barge	4	9	153	0.1	0.0	0.0
Other	89	272	4 418	2.6	0.8	0.9
Tug, Dredger, Pilot	812*	2 681	43 790	23.3	8.3	9.4
Total	3480	~32000	~470000	100	100	100

* Contains entries from smallest sources. Note, that **unidentified vessels are included** in this class.

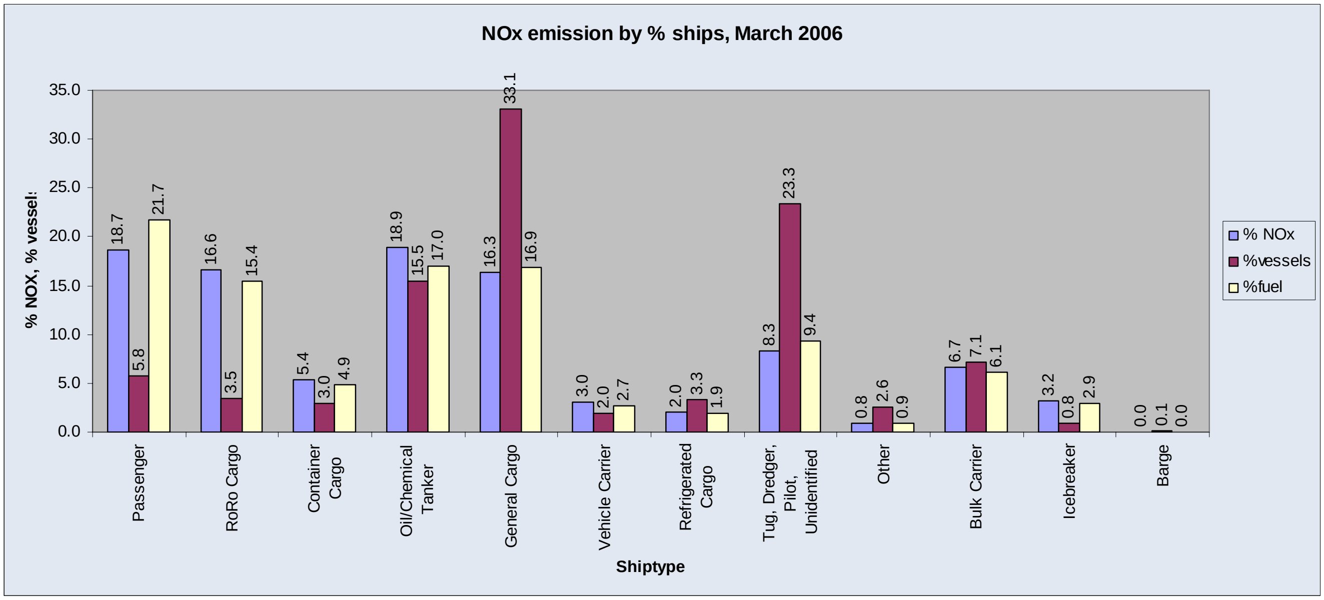

Figure 4: Proportional division of number of ships in each class, their fuel consumption and NOx production.

From **Figure 4** and Table 6 it can be seen that while passenger ships represent < 6 % of all vessels, their contribution to NOx emission is the highest. These cases reflect the feature seen in Figure 4 with abnormally large number of vessels falling into “Tug, Dredger, Pilot” category. This is because the default class for a ship is the smallest possible, making all unidentified ships appear as tugboats.

Table 7: The size classes of the ships sailing in the Baltic Sea region in March 2006.

Vessel size, GRT	**NOx output, tons**
GRT < 300	262
300 < GRT < 1000	829
999 < GRT < 2500	1 480
2499 < GRT < 4500	2 887
4499 < GRT < 8000	3 798
7999 < GRT < 12000	3 840
11999 < GRT < 21000	6 364
20999 < GRT < 50000	8 578
GRT >= 50000	2 429
Unknown	1 854
Total	~32 000

Table 7 lists the NOx output in each size class of ships. In March 2006 most NOx is produced by ships of second largest class, 21 000 ≤ GRT < 50 000.

Table 8: The age of the ships sailing in the Baltic Sea region in March 2006. DOB = Date of build

Build year	NOx, tons
2000-	10 472
1989 < DOB < 2000	8 544
1979 < DOB < 1990	7 052
1969 < DOB < 1980	3 968
1959 < DOB < 1970	317
DOB ≤ 1960	119
Unknown	1 854
Total	~32 000

Table 8 lists the NOx output of ships built in different decades. The largest NOx output is produced by ships built after the year 2000.

On annual level, based on the size distribution of the ships in the Baltic Sea, most of the NOx is emitted by ships of 8000 – 50 000 GRT (**Figure 5**). There are modest changes when a full year's data is compared to the data from March 2006 (**Table 7**).

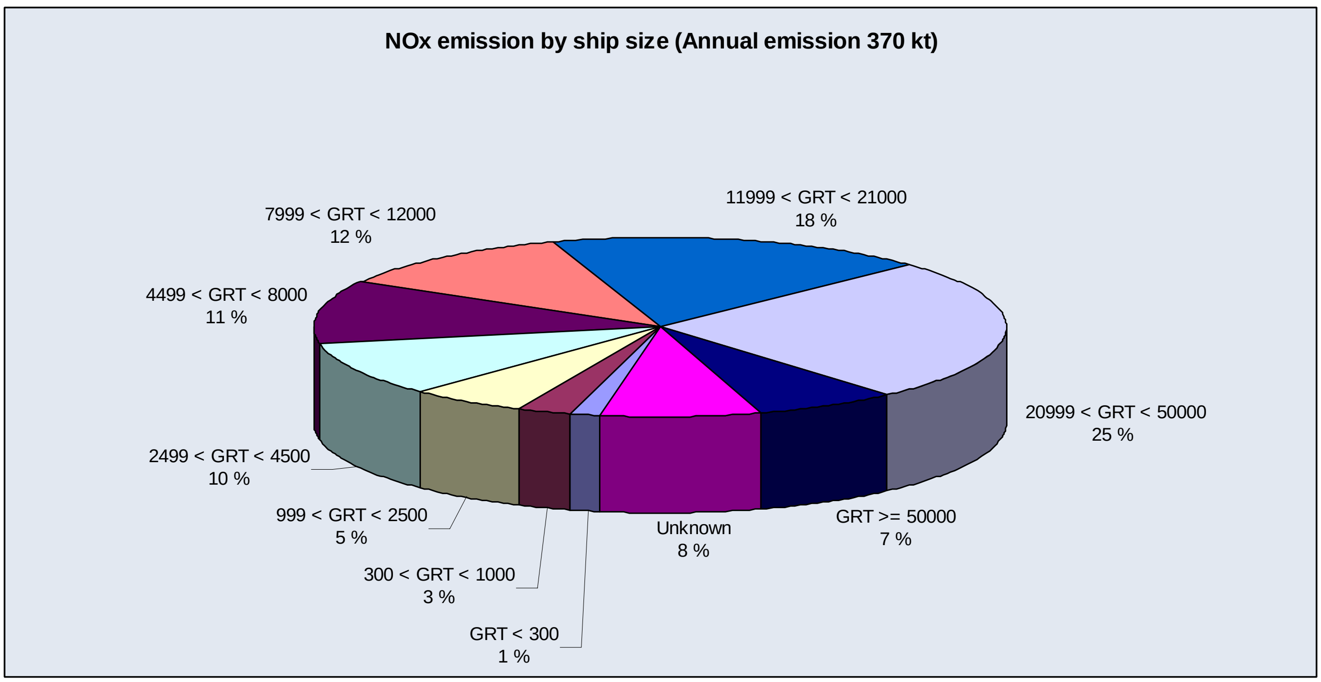

Figure 5: NOx emission by size category (annual emission is 370 kilotons)

These size classes combined are responsible for 55 % of the annual NOx emission. Similar observations can be made based on vessel age, where emissions from ships constructed after the year 1990 constitute almost 60 % of the total emission both annually and on monthly level (**Figure 6** and **Table 8**).

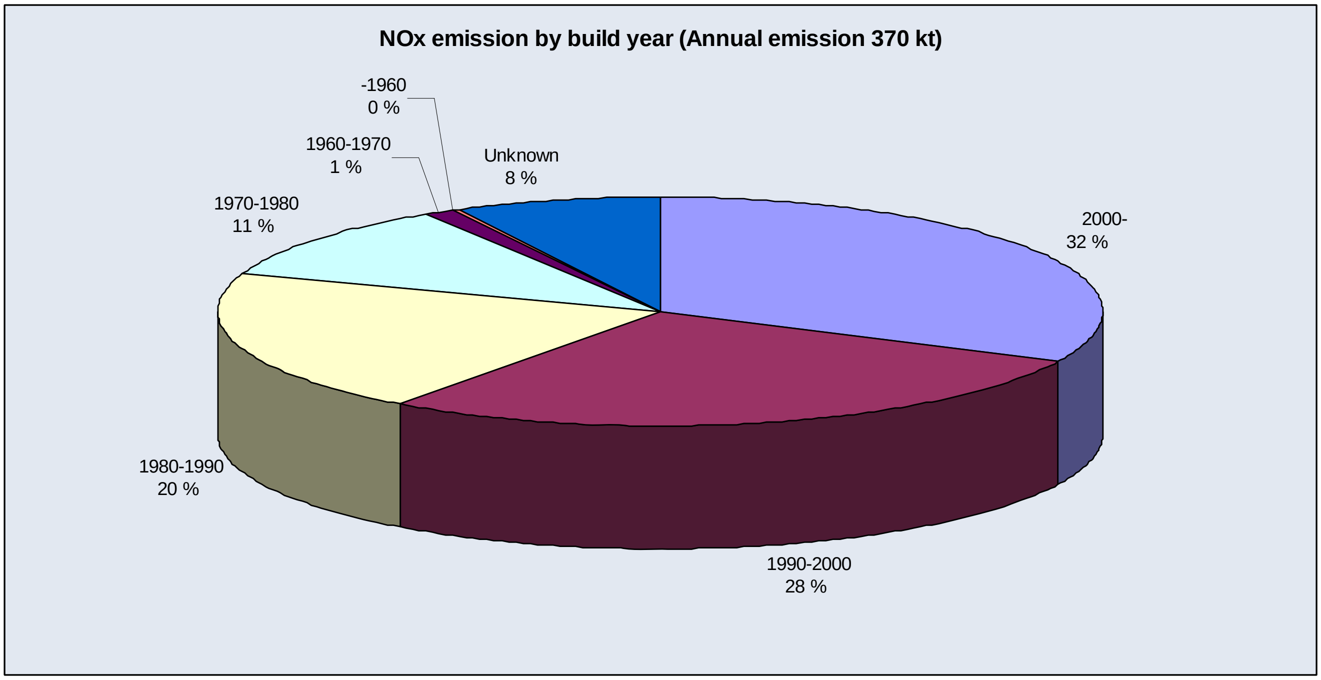

Figure 6: NOx emissions from ships of different age.

The emissions from individual ship types are shown in **Figure 7** and **Table 4**. It can be seen that some ship types, most notably passenger and RoRo cargo ships, produce significant amount of NOx when compared to the number of ships they represent.

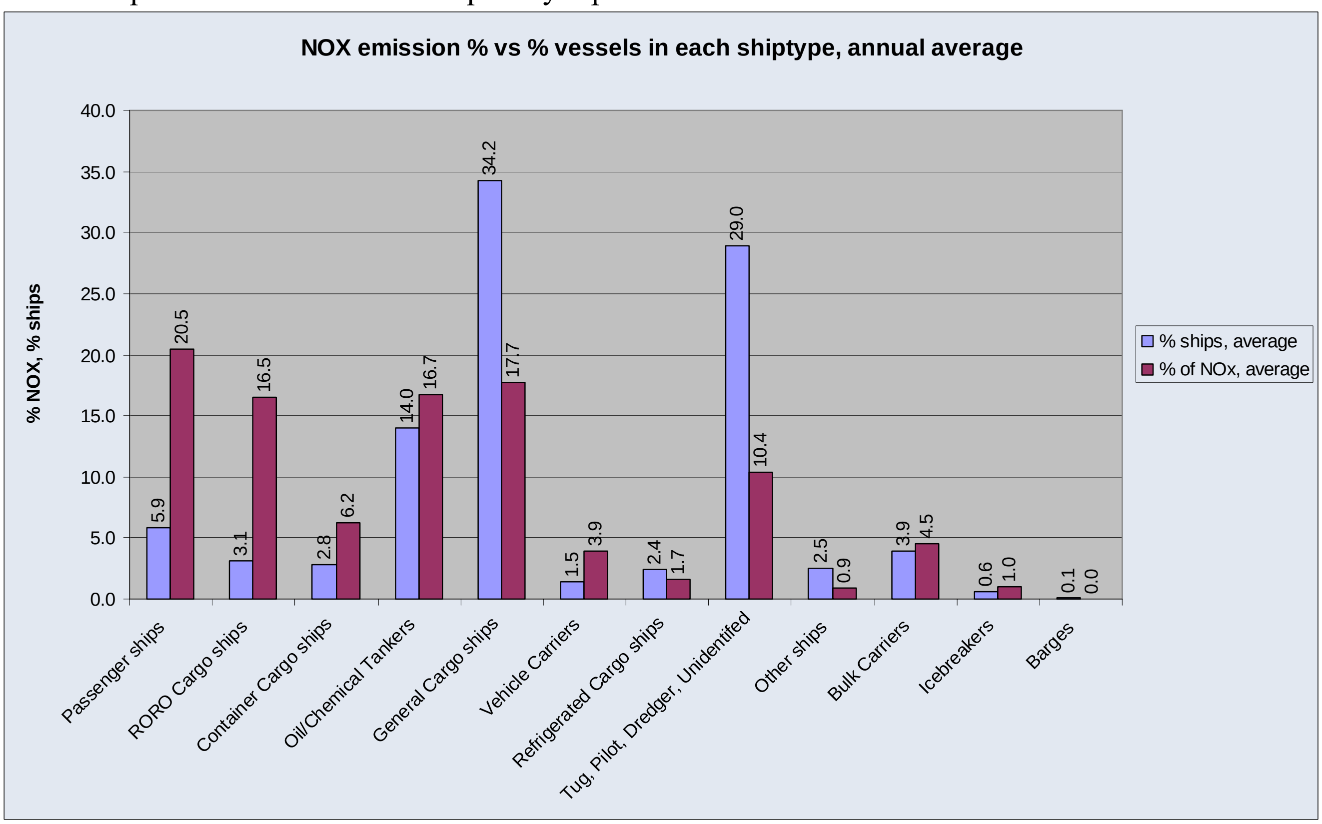

Figure 7: Contribution of ships to annual NOx output of 370 kt in each of the ship types compared to its proportion of the total number of ships.

For example, RoRo cargo ships represent ~3.1 % of all the ships, but produce ~16.5 % of the total

NOx emission. Here one should also note the large number of ships in the “Tug, Dredger, Pilot” class, which can be explained with inclusion of unidentified vessels in this class.

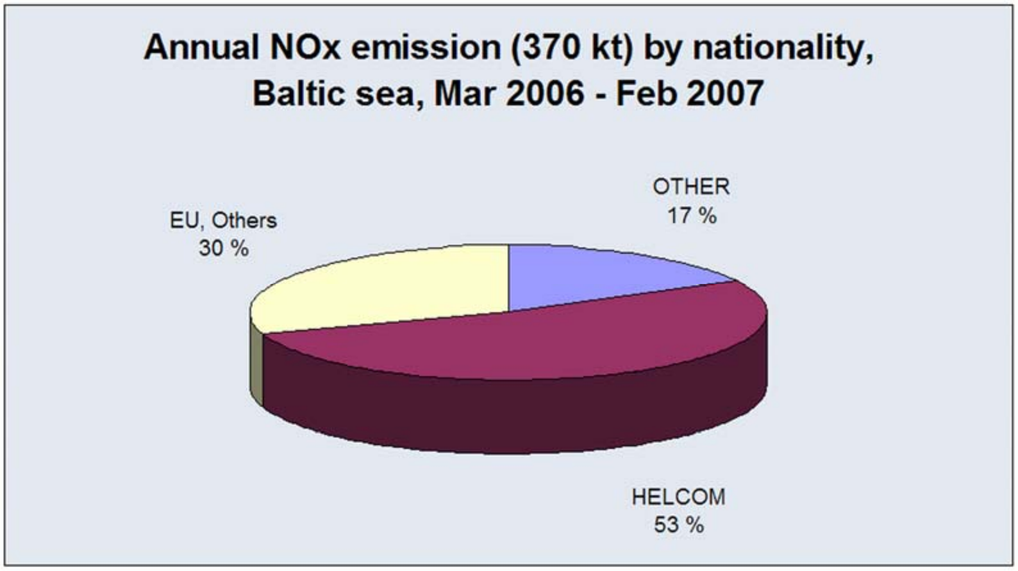

Figure 8: Distribution of emissions between HELCOM member states, EU countries outside HELCOM and vessels registered to other countries.

Figure 8 shows how the annual emission is distributed among vessels registered to different regions. As can be seen from this figure, more than half of the emission arises from ships registered to HELCOM member states, roughly one third from vessels registered to some other EU members and the remaining 17 % from ships of other countries. This division was made by investigating the Mobile Maritime Service Identity (MMSI) numbers and the country codes they contain.

For the full year of AIS data, following observations can be made based onTable 7, Table 8, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 :

1) Top three vessel classes that produce most NOx are (in order of most NOx produced)
   a) Passenger ships (20.5 %)
   b) General Cargo ships (17.7 %)
   c) Oil / Chemical Tankers (16.7 %)

2) The top three of the most NOx released size-class of ships are:
   a) 21000 – 50000 GRT (25.9 %)
   b) 12000 – 21000 GRT (17.9 %)
   c) 8000 – 12000 GRT (11.6 %)

3) The top three age classes that produce most NOx:
   a) 2000- (32.0 %)
   b) 1990-2000 (27.9 %)
   c) 1980-1990 (20.3 %)

4) Most of the annual NOx emitted from ships arises from vessels registered to HELCOM member states.

3.3. Comparison with data and experience of the shipping companies

Thirteen shipping companies' experts were interviewed in the process of developing the algorithm. The methodology and principles behind the algorithm were presented and factors affecting emissions of shipping were discussed and contribution algorithm development collected in qualitative manner.

Shipping companies' methods to calculate NOx emissions varies. One reason is the different type of vessels they are handling and the chosen factors suits best for them. Feedback collected from the experts has been considered in development process and programmed into algorithm when possible. The shipping companies agreed with the developers of the algorithm that the most significant factors for the NOx emission calculation have been programmed into the algorithm. Nevertheless there are some factors that have significant contribution to NOx emissions that have not been taken into account in the results so far and most of them increase the emissions.

In general, the shipping companies highlighted several issues that have an influence on the fuel consumption and therefore on NOx emissions:

1 Time schedule, engine load
- Ships are driving with lower engine load when possible to save fuel (load 50-70%). Minor decrease in ship velocity has a significant impact to needed engine load. Design speed can be maintained with 85% load. Load over 90% is rarely used and load over 95% could be considered maximum. Load higher than 95% would rise problems in engine use and would not considerably increase the speed.

2 Abatement technology

3 Sea currents and waves
- can increase significantly the fuel consumption

4 Ice conditions
- can increase significantly the fuel consumption
- behind ice breaker, in "a pipe", fuel consumption can be sometimes even lower than in normal conditions

5 Freight load, displacement of a ship
- Ships that replace the missing freight mass with ballast water - the effect is not significant (i.e. tankers)
- When empty ships have to trim their balance so that rear is deeper to keep propeller sufficiently under water - this diminishes the potential to save fuel when less freight onboard.

6 Shallow waters, squat phenomena
- Shallow shipping lanes affects losses in speed because of an squat effect between sea bottom and bottom of a ship

7 Wind, air resistance
- Ships that are vulnerable to air resistance are typically passenger vessels with large surface area
- Wind creates difficulties especially when maneuvering, head wind does not have a significant influence on fuel consumption.

As mentioned earlier the most important factors affecting emission calculations are taken into account in the calculation methods. The most important is the engine load which is considered in the algorithm more detailed than in traditional emission inventory calculations. Effect of wind and waves are under development thus not included in results in this document. Sea currents, ice conditions, amount of water under a ship (shallow water) and freight load (displacement) are not included.

Finnish shipping companies distributed data from their databases for the study purposes and quality assurance of the algorithm. Fuel consumption was chosen for the primary factor to be compared between shipping company data and the algorithm results. This is because fuel consumption is one factor that correlates with emissions and is being calculated by the algorithm. Fuel consumption is also important for shipping companies from economical point of view and therefore accurately recorded. Generally shipping companies have monthly fuel consumption records for a ship. Months that were studied were chosen to represent different conditions of a calendar year: March, July and November 2006.

Ships for QA were chosen to represent different ship types and so that the time on the Baltic Sea on studied months would be as long as possible. If a ship has left the study area the fuel consumption has been extrapolated to one month from the available data. When comparing algorithm results to real fuel consumption it can be seen that generally algorithm calculates less fuel consumption for main engines. There are only few cases when QA calculations show that the real fuel consumption has exceeded the calculated value. As an example fuel consumptions of the 11 passenger ships chosen for the QA study are collected in **Figure 9**. The left side column (turquoise) represents fuel consumption reported by a shipping company and the right side column a ShipNODeff result. In general the emission is underestimated but in three cases out of 11 ShipNODeff result is slightly higher than the real one. **Figure 10** shows results of several other ships in QA studies. From these results it is also possible to see that in general the ShipNODeff underestimates the emissions.

In case of auxiliary engines the QA calculations have shown that the algorithm calculates considerably more than the real consumption is. In case of passenger ships the difference is most considerable. Nevertheless, the total fuel consumption from the calculations exceed the real total consumption only in a few cases because generally the energy needed from auxiliary engines is much smaller than the pushing power on sea.

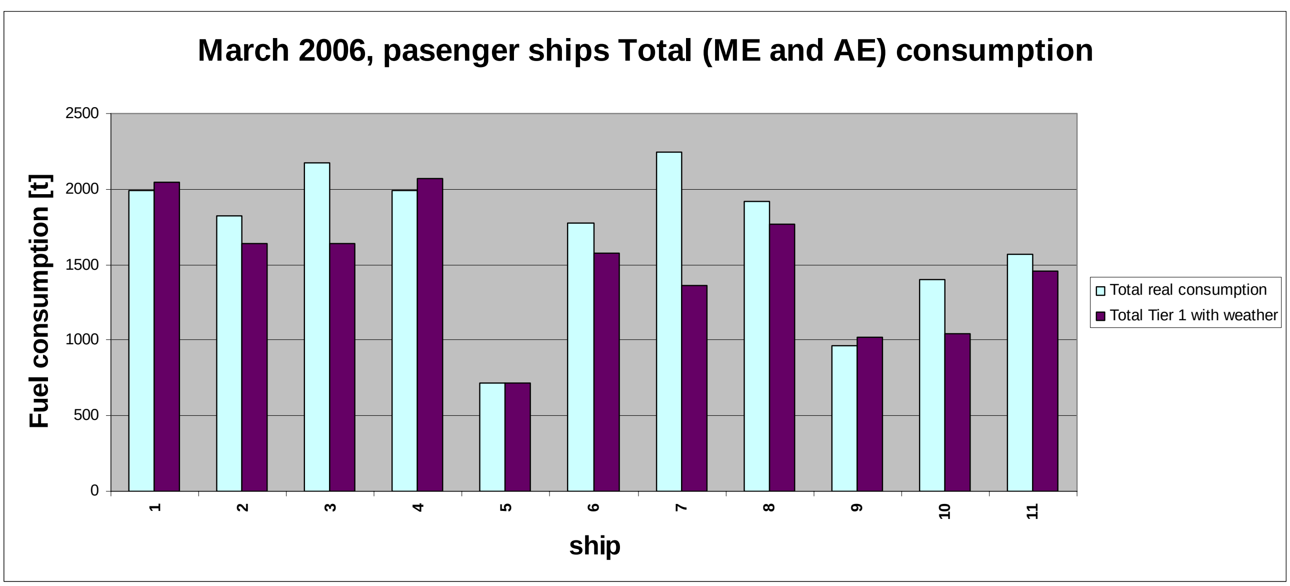

Figure 9: Comparison of total fuel consumption of 11 passenger vessels to ship owner data, March 2006.

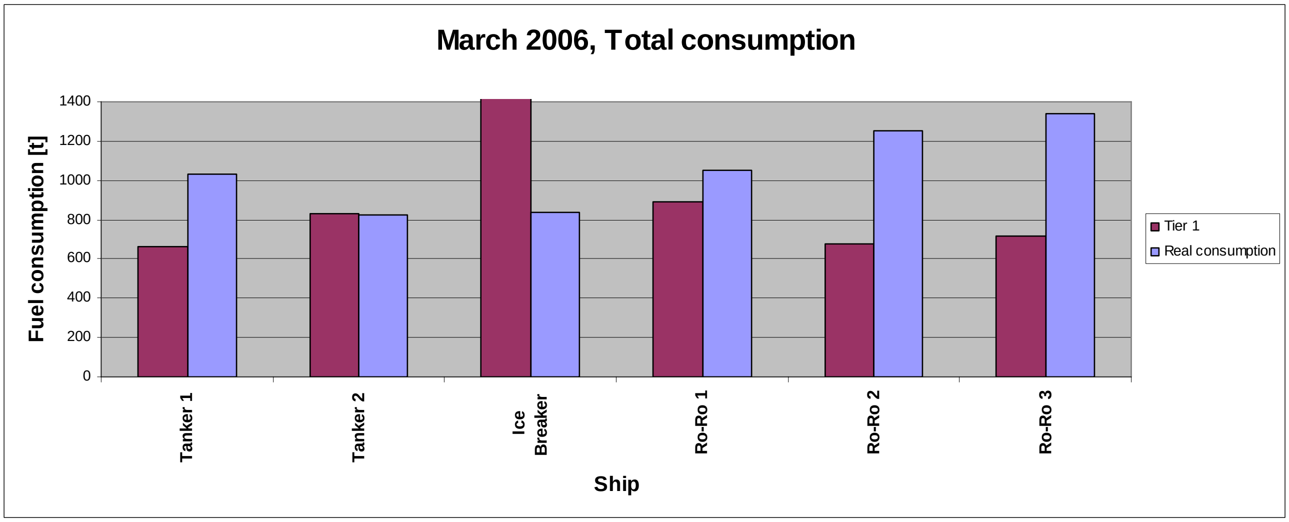

Figure 10. Comparison of total fuel consumption of several ships to ship owner data, March 2006.

4. Comparison of NOx emission from shipping with NOx emission from land-based sources and other estimates

4.1. Shipping vs. land-based sources

NOx emission from shipping compared to land-based emissions as t/grid square on the first level of the model in March and June 2006 are presented in **Figure 11**. Inside the chemistry-transport model the emissions have seasonal, weekly and diurnal time variation coefficients and vertical emission profiles which depend on the emission sector and country. Diurnal emission factors depend on the local time of the grid.

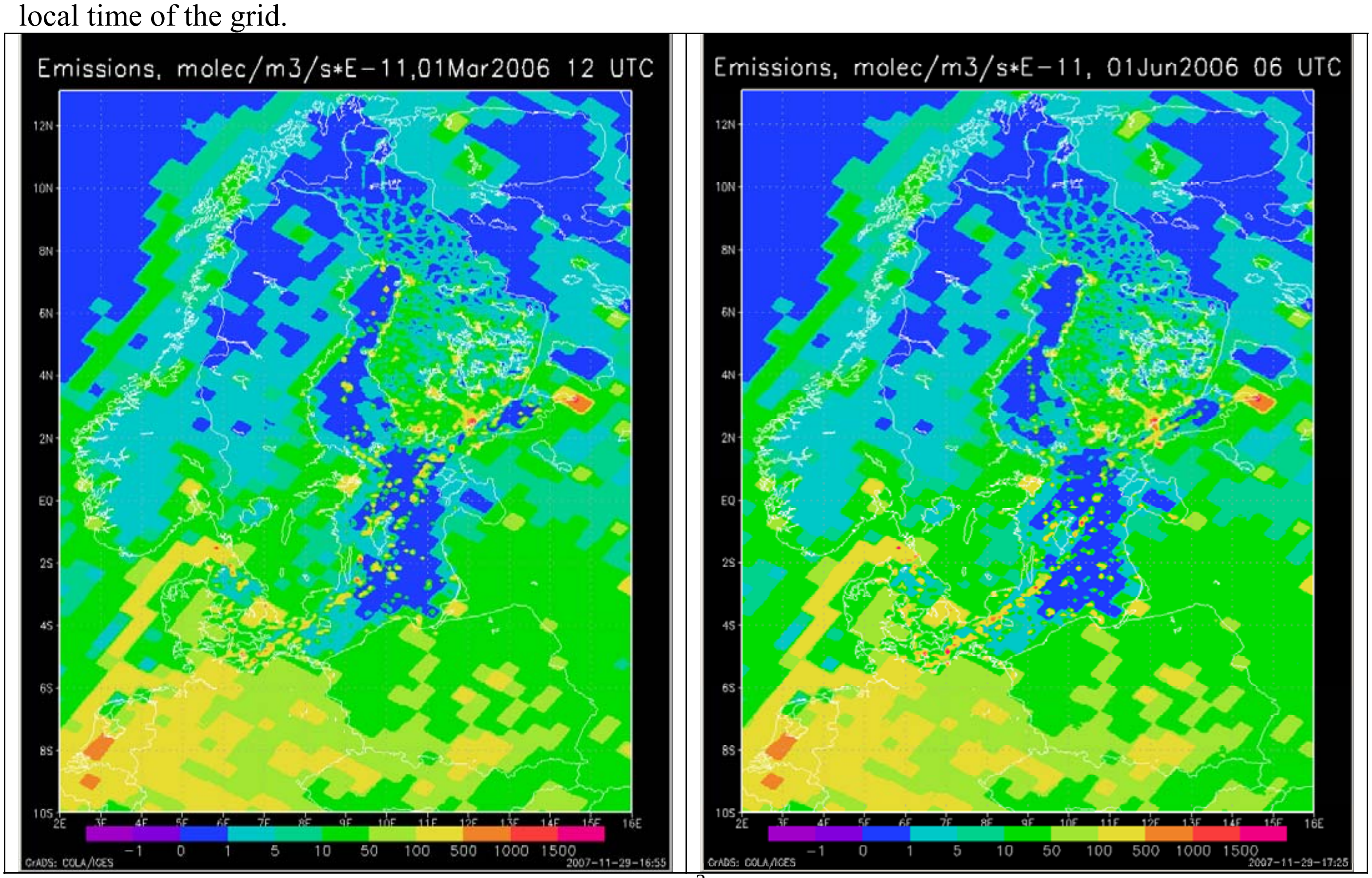

Figure 11: Relative emission intensities, molecules/m³/s at first model level on beginning of March and June 2006.

Emissions have been calculated using the annual gridded emissions of the EMEP emission data base with resolution of 50 km x 50 km and 11 S-emission sectors (www.emep.int), using the Finnish emission inventory of the Finnish Environmental Institute, SYKE (annual emissions divided to spatial sources of 1 km grid and individual point sources with stack parameters to estimate the effective emission heights) and ship emissions with 15 min. time interval (in around 9 km grid); all of them have been converted to areal emission intensity (**Figure 11**). EMEP ship emission estimate is based on report Cofala et al., 2007. According to it, NOx emissions from larger vessels were 299 kt NOx and 212 kt SO_2, and emission of all vessels 315 kt NOx and 224 kt SO_2 in 2000.

According to EMEP status report 1/2007 (Tarrason et al., 2007) source-receptor relationship matrices, total NOx deposition to the Baltic Sea (BS) in 2005 was 130.1 kt nitrogen (N) and total NHx-deposition 94.1 kt N. Highest contributors to this deposition were as listed in Table 9.

Table 9: Highest contributors to the N deposition to the Baltic Sea (Tarrason et al, 2007). Italics and parentheses indicate data where doubts about the accuracy of the deposition have been raised.

2005	**oxidized N deposition to BS (100 ton N)**	**reduced N deposition to BS (100 ton N)**	**total**	**Emission (kton)**	
				NOx	**NHx**
BS shipping	183	-15	168	343	0
Germany	176	196	372	1433	619
Poland	116	141	257	811	326
Denmark	59	107	166	186	93
England	109	26	135	1627	318
Sweden	61	70	131	205	52
Russia[‡]	*(94)*	*(35)*	*(129)*	*(3093)*	*(621)*
Finland	45	59	104	177	36
France	49	44	92	1207	732
Ukraine	32	38	70	960	550
Netherlands	39	30	69	344	135

The emission trends for the countries contributing the most to the deposition are presented in **Table 10**.

[‡] The data in brackets will be clarified at a later stage.

Table 10: Emission trends (kton NO_2) of the countries contributing by the biggest share to the airborne NO_x deposition to the Baltic Sea (Tarrason et al., 2007). Italics and parentheses indicate data where doubts about the accuracy of the emissions have been raised.

	1990	1995	2000	2001	2002	2003	2004	2005	2010
BS	236	268	303	311	318	327	335	343	361
Germany	2878	2131	1855	1763	1647	1605	1554	1443	1081
Poland	1581	1121	838	848	796	808	804	811	879
Denmark	266	253	188	184	181	189	171	186	127
England	2932	2355	1837	1799	1693	1685	1621	1627	1181
Sweden	306	271	217	211	206	203	197	205	148
Russia[§]	*(3600)*	*(2570)*	*(2457)*	*(2582)*	*(2698)*	*(3105)*	*(3093)*	*(3093)*	*(2758)*
Finland	299	258	235	220	208	218	205	177	170
France	1829	1643	1390	1335	1282	1243	1218	1207	860
Ukraine	1753	1245	861	886	911	936	960	960	1222
Netherlands	549	464	389	381	368	367	360	344	244

4.2. Comparison of emission inventories for the Baltic Sea shipping

There are only few calculations for NOx emissions and fuel consumption of shipping in the Baltic Sea. The emission inventories of ENTEC [Janusz Cofala J., et al., 2007] and BMT [Davies B. M. et al., 2000] are compared with the inventory of ShipNODeff in the **Table 11**.

Table 11 Emission inventories for the Baltic Sea

NOx	**ENTEC (for year 2000)**	**BMT (for 2001)**	**ShipNODeff (March 2006 – Feb 2007, 12 months)**
Vessels over 500 GRT	299 kt		
Vessels under 500 GRT	16 kt		
Vessels under 1000 GRT (March 2006)			1.1 kt
Vessels under 1000 GRT[**]			13 kt
Vessels over 1000 GRT			357 kt
Vessels under 300 GRT (March 2006)			0.262 kt
Vessels under 300 GRT[††]			3 kt
all vessels	315 kt	365 kt *	370 kt
Fuel consumption [PJ][‡‡]	153 PJ (vessels over 500 GRT)	215 PJ	226 PJ
Fuel consumption [kt]		5301 kt *	5581 kt

* Vessels over 250 GRT

Table 11 shows that ShipNODeff has the highest estimate for NOx emissions in the Baltic Sea. ENTEC and BMT estimates are for the years 2000 and 2001, respectively. ENTEC has also estimated the growth rate for NOx which does not explain the higher emission of ShipNODeff. ENTEC methodology [Entec 2002, 2005a,b] to calculate ship emissions in the Baltic Sea is focusing

[§] The data in brackets will be clarified at a later stage.
[**] extrapolated to 12 months
[††] extrapolated to 12 months
[‡‡] energy content of HFO was used for BMT and ShipNODeff, 40.6 MJ/kg

on port calls to and from EU countries with certain assumptions that leaves out shipping traffic. ShipNODeff calculation is based on real ship traffic including all ships with operational AIS transponder. Nevertheless, ShipNODeff annual fuel consumption in the Baltic Sea is underestimated. This can be seen from QA results in Section 2 of this document. It can also be concluded that NOx emissions are underestimated because NOx calculation in the algorithm is based on power need, similarly as fuel consumption. This means that the real emissions are more than 370 kt of NOx from shipping on Baltic Sea and higher than previous estimates.

5. First estimates the contribution of NOx emission from shipping to the eutrophication of the Baltic Sea.

5.1. Dispersion and deposition of emissions

The transport, turbulent diffusion, chemical transformation and deposition of nitrogen and sulphur compounds in the Baltic Sea region have been calculated with the three-dimensional grid model HILATAR (http://www.fmi.fi/research_air/air_25.html) developed at the Finnish Meteorological Institute (FMI). The model is verified by comparing the results with measurements at over 90 EMEP stations over several years (Hongisto et al., 2003), with model-model intercomparison study (Zlatev et al., 2001) and with BASYS (Baltic Sea System Study) ship and coastal measurements (Schulz et al., 1999).

We use a model with resolution of 9 km or less combined with regional scale (Europe) background calculations. The meteorological input fields are provided by the operational HIRLAM (HIgh Resolution Limited Area Model) weather prediction model of the FMI. We use meteorological fields from 17 vertical levels below 3 km and 3 additional levels over it, the highest at the height of around 10 km. The stability parameters are calculated from the pressure, temperature and humidity profiles and accumulated momentum fluxes based on the HIRLAM forecasts. The gridded European emissions are based on the EMEP emission database covering Europe and the local emission inventory generated by the Finnish Environmental Institute and maintained by FMI. For the marine part, the EMEP emissions from shipping have been replaced with the emissions presented in this report.

The model calculates gaseous and particle concentrations and deposition (dry and wet) for NO(g), NO_2(g), HNO_3(g), NO_3(p), PAN(g), NH_4NO_3(p), NH_3(g), SO_2(g), SO_4(p) and $(NH_4)1.5SO_4$(p). The results of the European scale model runs are used as the lateral boundary condition for the horizontal advection to estimate the long-range transported contribution to the model results.

Two model runs were performed, one with the ship emissions included and one without any emissions from shipping. The difference in the annual deposition of oxidized nitrogen (NOx) between these two runs is depicted in **Figure 12**. Figure 12 shows that part of the total NOx deposition in the Baltic Sea area that originates from shipping.

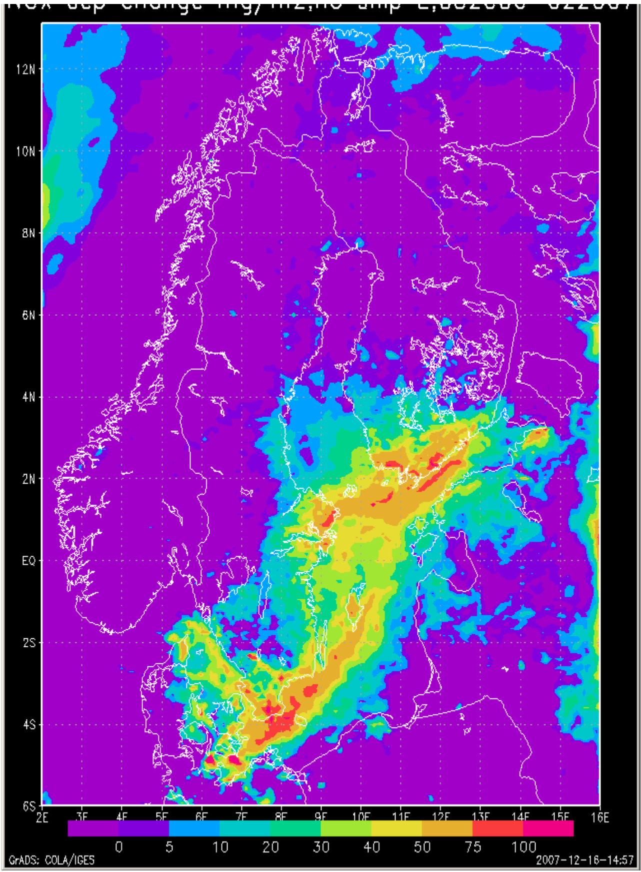

Figure 12: Annual NOx deposition caused by ship emissions (mgN/m²) calculated as the difference between the modelled deposition with and without the NOx emissions from shipping in the period 1.3.2006-28.2.2007.

Figure 13 depicts the percentage of the deposition caused by shipping emissions relative to the total deposition. The percentage is highest in the northern Baltic Proper because of the higher deposition from other sources in the southern Baltic Sea.

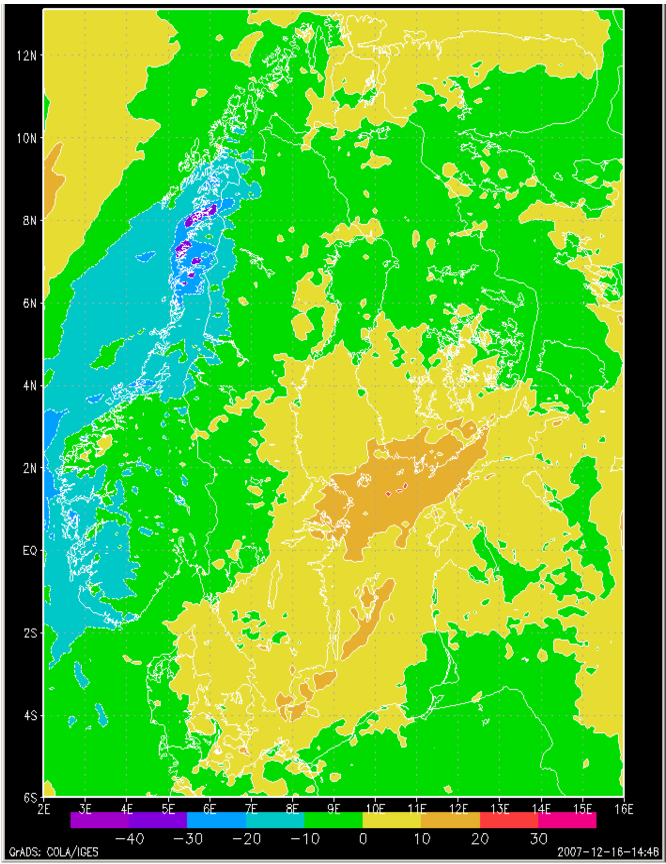

Figure 13: Percentage of annual NOx deposition caused by ship emission calculated as the difference between the modelled deposition with and without the NOx emissions from shipping.

However, due to the structural changes that the atmospheric boundary layer above the sea undergoes during the year, the relative effect of the shipping emissions on the deposition varies widely with season. **Figure 14** illustrates the relative contribution from shipping (cf. Figure 13) in the winter and summer. According to the figure, in the mid-summer (when the marine ecosystem in the Baltic Sea is most receptive to external nutrient input), up to 50% of the NOx deposition in the northern Baltic Proper can originate from shipping.

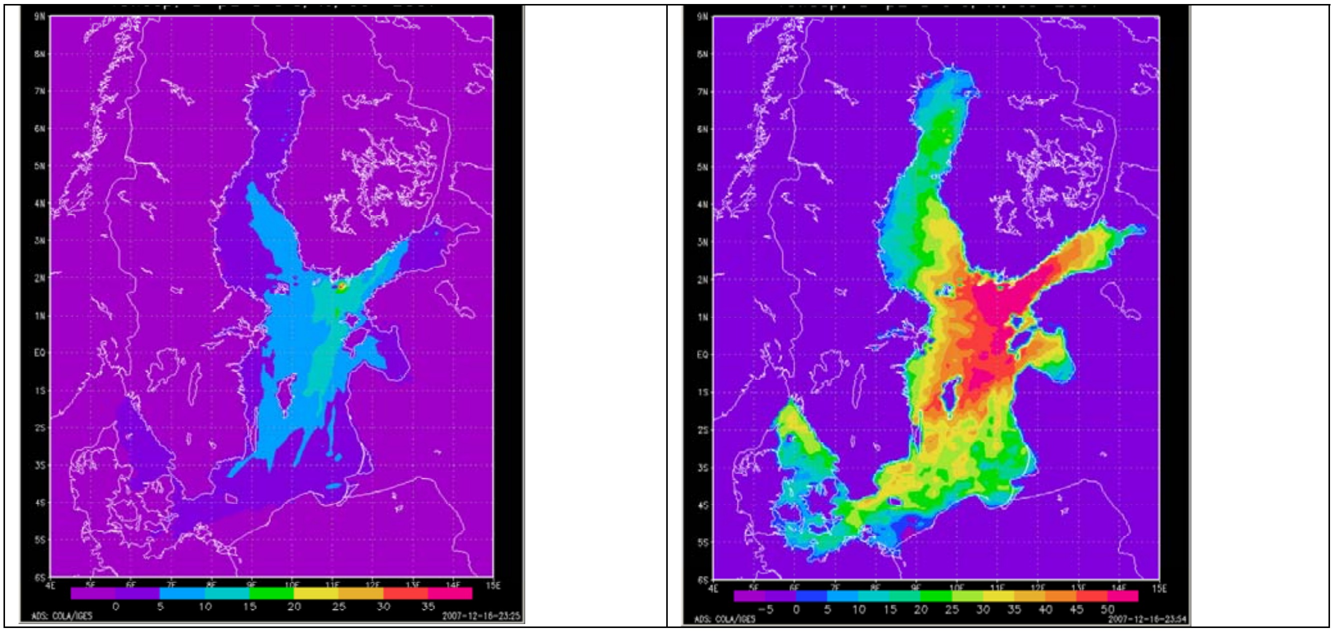

Figure 14: Percentage of monthly NOx deposition to the Baltic Sea caused by ship emissions (left: January 2007, right: July 2006) calculated as the difference between the modeled deposition with and without the NOx emissions from shipping.

5.2. Contribution to Baltic Sea eutrophication

The Baltic Sea is strongly affected by eutrophication. The Baltic Marine Environment Protection Commission (HELCOM), consisting of the governments of the Baltic Sea countries and the European Community, has defined two of its four main objectives as "Baltic Sea unaffected by eutrophication" and "Maritime activities carried out in an environmentally friendly way" to be met by 2021. The HELCOM Baltic Sea Action Plan (http://www.helcom.fi/BSAP/en_GB/intro/) identifies eutrophication as a major problem in the Baltic Sea.

Since the 1900s, the Baltic Sea has changed from an oligotrophic clear-water sea into a eutrophic marine environment. Eutrophication is a condition in an aquatic ecosystem where high nutrient concentrations stimulate the growth of algae which leads to imbalanced functioning of the system, such as:

- intense algal growth: excess of filamentous algae and phytoplankton blooms,
- production of excess organic matter,
- increase in oxygen consumption,
- oxygen depletion with recurrent internal loading of nutrients, and
- death of benthic organisms, including fish.

Excessive nitrogen and phosphorus loads coming from land-based sources, within and outside the catchment area of the Contracting States, are the main cause of the eutrophication of the Baltic Sea. About 75% of the nitrogen load and at least 95% of the phosphorus load enter the Baltic Sea via rivers or as direct waterborne discharges. About 25% of the nitrogen load comes as atmospheric deposition.

The primary production in the Baltic Sea is mostly limited by the availability of nitrogen. This means that an addition of nitrogen (as, for example, deposited from the atmosphere) will to lead to an increase in primary production, leading further to an increase in the level of eutrophication.

Atmospheric nitrogen deposition is estimated to contribute about 25-30% of the total nitrogen input to the Baltic Sea. The nitrogen deposition includes also the NOx emissions from shipping, which are transformed by atmospheric reactions on their way from the ship chimney to the site of deposition.

However, the dynamic nature of the Baltic Sea ecosystem causes one dose of atmospheric deposition to have different effects, depending on the exact deposition compound, the time of the year, the nutritional status of the year, and most likely to some extent, the prevailing plankton community in the sea. Therefore, the estimation of dose-effect relationships must be based on their effects in the real-time.

Figure 15 is a calculation of the effect of nitrogen emissions from shipping on the surface nitrate concentrations in the Baltic Sea. The calculation is based on an instantaneous nitrate concentration field, upon which a field of nitrogen emissions is added with the assumption that the emission is distributed in the emission grid to 9*9 km grid cells and in the vertical to a depth of 10 meters (the typical mixing depth in the summertime Baltic Sea). The nitrogen emission used is the cumulative emission for one month.

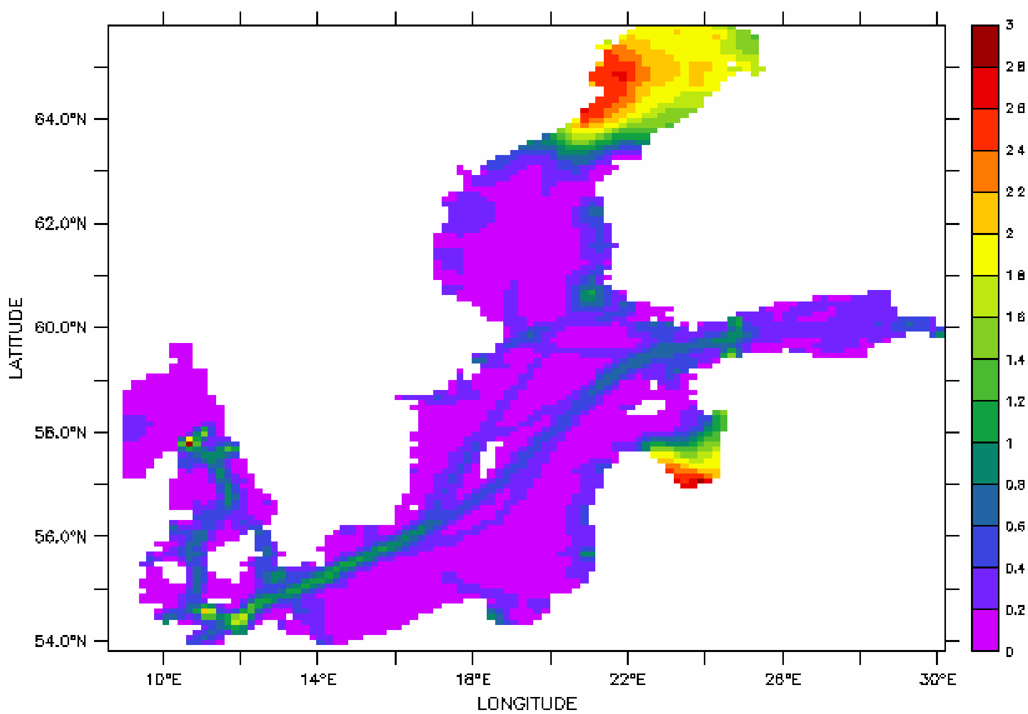

*Figure 15: The surface (0-10 m) nitrate concentration in the Baltic Sea on July 20, 2006, as seen by the operational ecosystem model of the Finnish Institute of Marine Research (FIMR). On top of the background concentrations, the emission from shipping is accumulated for one month and mixed into top 10 meters of the water column over the emission calculation grid cells (9*9 km).*

Figure 15 serves to demonstrate the order of magnitude of the nitrogen emissions from shipping: the monthly total emissions add up to a concentration that is comparable to, if not in excess of the natural levels found in the sea in the summer. The monthly accumulated nutrient concentration amounts to about 10-20 % of the winter concentration in the main shipping lane.

An estimate utilizing the modeled deposition is the topic of an on-going study.

6. NOx emission from ships according to the IMO "Three Tier Approach"

6.1. The IMO "Three Tier Approach"

Tier I emission estimate

In the calculations for the baseline NO_x emission estimate the NO_x emission procedure has been refined. In these calculations the NO_x emission in g/kWh is calculated using the IMO regulation curve for marine diesel engines. These are:
a) 17.0 g/kWh when the maximum engine speed is less than 130 rpm;
b) $45.0 * n^{(-0.2)}$ g/kWh when the maximum engine speed (n) is more than 130, but less than 2000 rpm, and
c) 9.8 g/kWh when the max engine speed is greater than 2000 rpm.

For these equations, the engine speed is required. This can usually be obtained from the shipping register. In the baseline NO_x emission calculations the IMO curve has also been applied to old engines manufactured before 1990. These regulations only apply to new engines, but due insufficient measurement data of old engines and their NOx output, it has been assumed that old engines conform to Tier I regulations.

NOx emission scenario for Tier II

The proposed Tier II NOx regulations suggest that a diesel engine, which is installed on a ship constructed on or after 01.01.2011, should further reduce their NO_x emission with 2 – 3.5 g/kWh. It is not clear yet what the number will be, and will it be different for 2-stroke and 4-stroke engines. In Tier II scenario it has been assumed that a 2 g/kWh reduction will apply to all diesel engines which are installed on a ship constructed on or after 01.01.2011. The NO_x emission coefficient for engines installed before this date is estimated as in baseline NO_x emission estimate.

NOx emission scenario for Tier III

The Tier III scenario is under discussion and at least three options have been proposed in document BLG 11/WP.4. In this report option A, i.e. the suggestion by Japan, has been taken into consideration. This suggests 80% reduction from Tier I in NO_x emissions for all engines. To simplify the calculations, the 50 nautical mile limit has been disregarded, since vessels most of the time travel within 50 nautical miles from the shore in the Baltic Sea. The 80% reduction from Tier I is imposed on all diesel engines which are installed on a ship constructed on or after 01.01.2015. In this case too, older engines are treated as described in baseline NO_x emission estimate.

The Tier III scenario suggested by Japan suggests that all diesel engines, which are installed on a ship constructed on or after 01.01.2015 should decrease their emission of NOx by 80 % relative to Tier I when within 50 nautical miles from shore.

6.2. Future scenarios

6.2.1. Traffic growth 2.6%

It is possible to demonstrate the effects of the three-tier approach with example calculations that are based on simplifying assumptions. The following scenarios are calculated until the year 2030 by using the monthly average amount of ships, 3774, and the total NOx emission of 370 kt in the Baltic in 2006 as a baseline. It has been assumed that there is a constant traffic increase of 2.6% and a constant renewal rate of 4% of ships. Tier II is calculated as 19% reduction, which corresponds with the reduction of 2.5 g/kWh from Tier I, based on the results and modeling principles used in ShipNODeff project.

A theoretical average emission of a ship for the year 2006 has been calculated and used when calculating an average emission of a ship for each year from 1986 to 2030. It has been assumed that the old ships count out from the year emission due to renewal represents theoretical average of 20 years old ship. Different methods to evaluate the average emission of a 20 years old ship have been used to demonstrate the considerable effect that the emission of an old ship left out from the calculation has to the results. These methods are marked as "abatement" percentage in the scenarios. Abatement of 2% until year 2011 (yellow trend in the **Figure 16**) has been used in all scenarios except one. The abatement has been stopped to the year 2011 when it is assumed that the functional development of engines stops. The scenario 5 is calculated with a constant emission for Tier I ships and ships built before 1.1.2000 are considered to have 10% more NOx emissions than the Tier I ships (turquoise trend in the Figure 16). New ships added to the Baltic fleet are calculated with an average ship emission of the current year including possible Tier effect. The traffic increase has been calculated with the average emission of a ship of the current year.

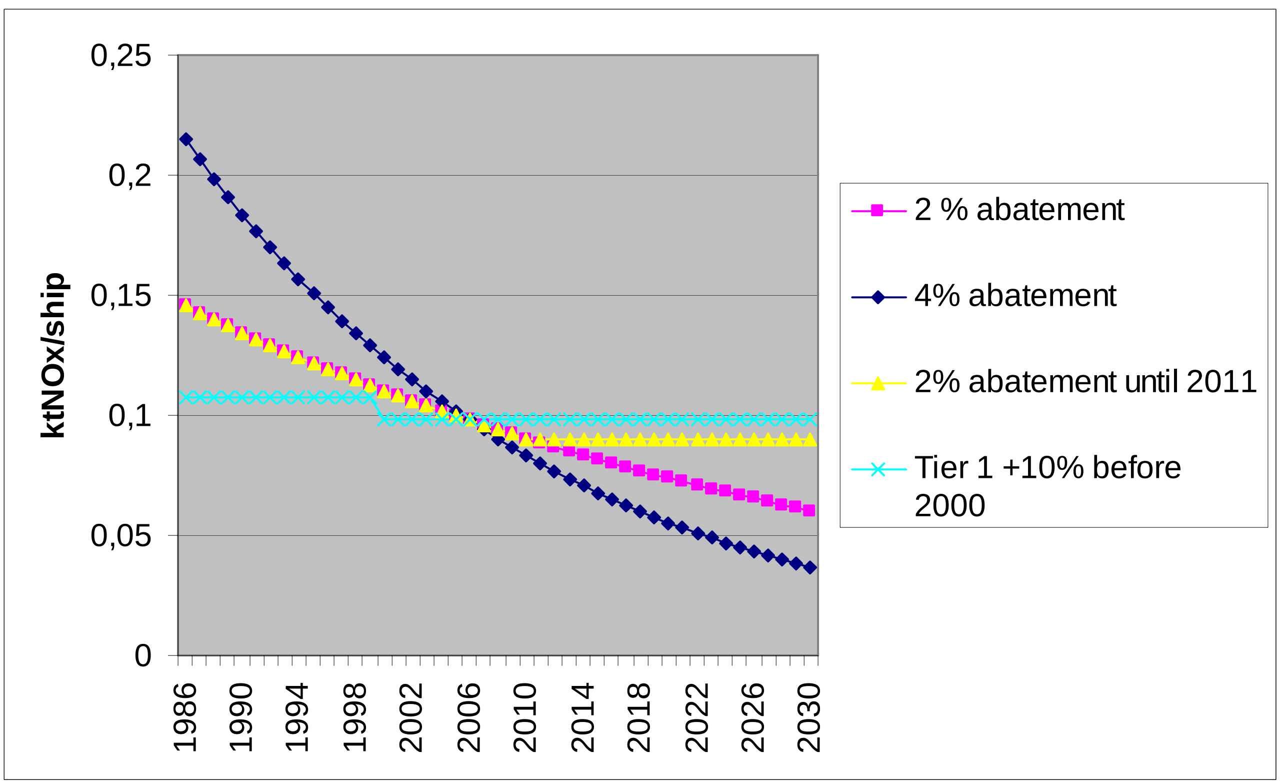

Figure 16. The four different methods to estimate the emission of NOx of an old ship left out from the annual emission due to renewal of the ships.

Five different scenarios have been calculated with above mentioned assumptions and summarized in the **Table 12**. The **Figure 17** shows the trend lines of the scenarios. It can be seen that with the traffic increase of 2.6% and the renewal rate of 4 % the trend will end in 531 kt of NOx in 2030. If only Tier II has been applied the value in 2030 is 435 kt and the trend is increasing. If Tier II and Tier III (Tier III with 50% reduction) are applied the total emission in 2030 is 311 kt and decreasing. If Tier II and Tier III (Tier III with 80%reduction) are applied the total emission is 190 kt and decreasing. If the percentile abatement is not used and we use the Tier I level average emission for ships after 1.1.2000 and Tier I average plus 10% for ships before 1.1.2000 (as shown in the Figure 16) the result for the year 2030 is 227 kt when both Tier II and Tier III (80% reduction) are applied.

Table 12. Results of the scenario calculations for 2.6% traffic increase.

	Assumptions	**Applied regulations**	**Year 2030**	**Trend line**
Scenario 1	Abatement 2% until 2011, renewal rate 4%, traffic increase 2.6%	No Tier II or Tier III applied	531 kt of NOx	increasing
Scenario 2	Abatement 2% until 2011, renewal rate 4%, traffic increase 2.6%	Tier II	435 kt of NOx	increasing
Scenario 3	Abatement 2% until 2011, renewal rate 4%, traffic increase 2.6%	Tier II and Tier III with 50% reduction	311 kt of NOx	decreasing
Scenario 4	Abatement 2% until 2011, renewal rate 4%, traffic increase 2.6%	Tier II and Tier III with 80% reduction	190 kt of NOx	decreasing
Scenario 5	Tier I average after 1.1.2000 and Tier I average plus 10% for ships before 1.1.2000, traffic increase 2.6%	Tier II and Tier III with 80% reduction	227 kt of NOx	decreasing

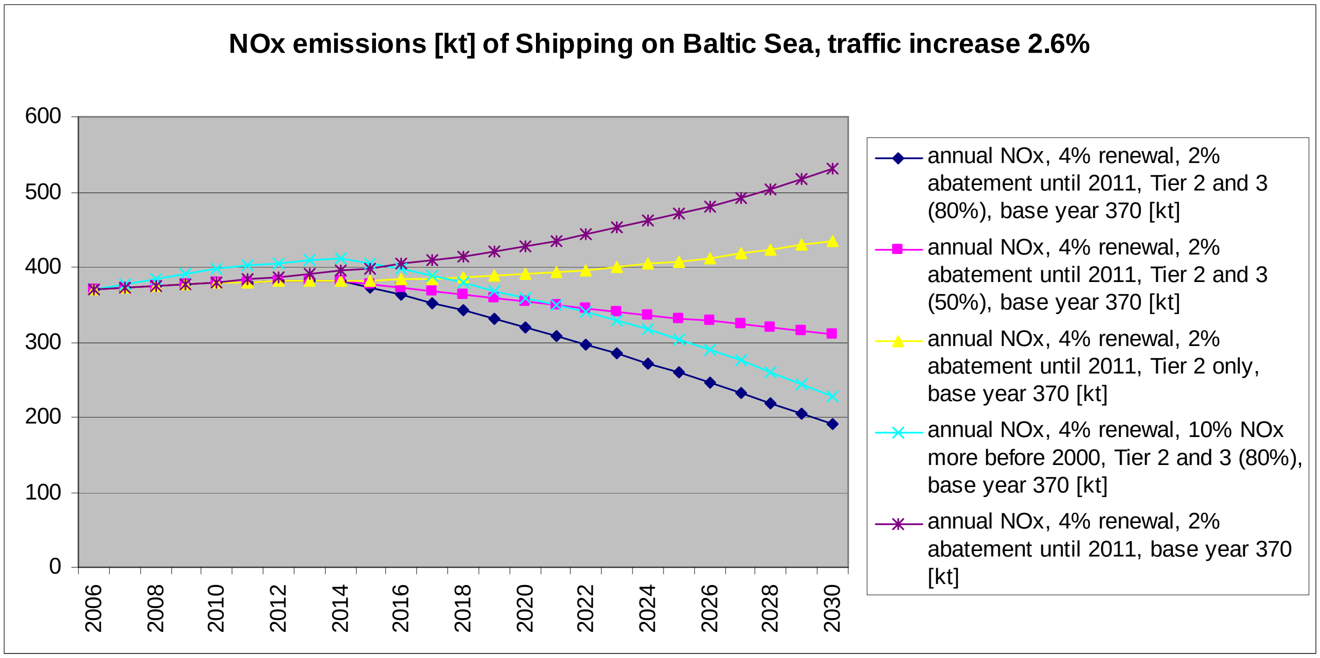

Figure 17. The five example calculation scenarios with 2.6% traffic increase.

6.2.2. Traffic growth 5.2%

Traffic growth is a major factor affecting the NOx emission trend and consequently, the emission level in 2030. To demonstrate the effect of the traffic growth, a growth rate of 5.2% is used for all scenarios in **Figure 18**. Only the scenarios 4 and 5 which both have 80% reduction in Tier III will show a decreasing trend in 2030.

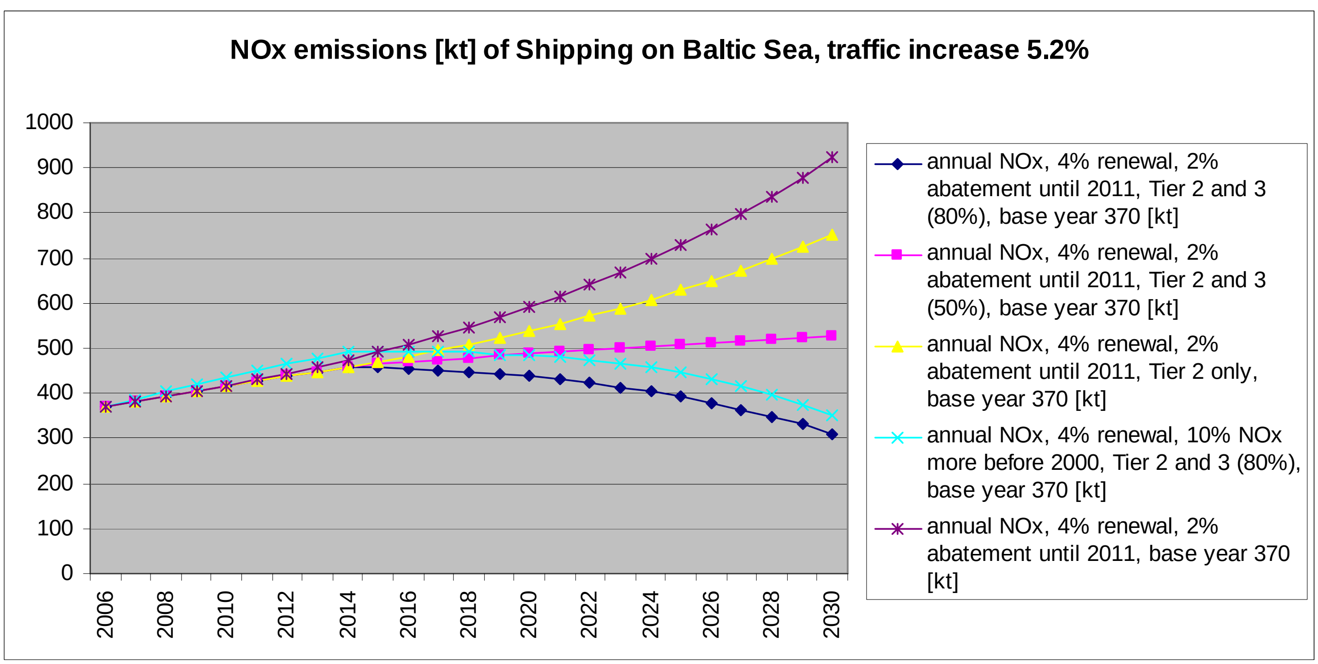

Figure 18. Scenarios with the traffic growth of 5.2%.

References

Janusz Cofala, Markus Amann, Chris Heyes, Fabian Wagner, Zbigniew Klimont, Max Posch, Wolfgang Schöpp Leonor Tarasson, Jan Eiof Jonson, Chris Whall, Andrianna Stavrakaki, 2007. *Analysis of Policy Measures to Reduce Ship Emissions in the Context of the Revision of the National Emissions Ceilings Directive*. Final report, 64 p.

Davies M E, Plant G, Cosslett C, Harrop O, Petts J W., Study on the economic, legal, environmental and practical implications of a European Union system to reduce ship emissions of SO2 and NOx. Final report. August 2000. BMT Murray Fenton Edon Liddiard Vince Limited. No. 3623. 56 p.

Entec (2005a), European Commission Directorate General Environment Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments. *Task 1 – Preliminary Assignment of Ship Emissions to European Countries*. Final Report Entec UK Limited, August 2005.

Entec (2005b), European Commission Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments. *Task 2 – General Report*, Final Report, Entec UK Limited, August 2005.

Hongisto, M., 2003. Hilatar, a limited area simulation model for acid contaminants. Part I. Model description and verification. Atmospheric Environment 37/11 pp. 1535-1547

Hongisto, M., Sofiev, M. and Joffre S., 2003. Hilatar, a limited area simulation model for acid contaminants. Part II. Long-term simulations results. Atmospheric Environment 37/11 pp. 1549-1560

Schulz, M., M. Ferm, M. Hongisto, K. Jylhä, G. Leeuw, Marks R., Plate E., Tamm S., Sopauskiene D ja Ulevicius V., 1999. Atmospheric nitrogen input to the Baltic Sea. Zuelicke C., (toim.) Proc. of the Third BASYS Annual Sci. Conf., s. 60-67.

Tarrasón, L, Fagerli H, Jonson, J E, Simpson, D, Benedictow, A, Klein, H, Vestreng, V, Aas, W and Hjelbrekke, A-G, 2007. Transboundary acidification, eutrophication and ground level ozone in Europe in 2005, EMEP status report 2007, 147 p.

Zlatev Z., Bergströn R., Brandt J., Hongisto M., Jonson J.E., Lagner J. ja Sofiev M., 2001. Studying sensitivity of air pollution levels caused by variations of different key parameters. TemaNord 2001:569. Nordic Council of Ministers, Copenhagen 2001. 47 s.

Acknowledgements

We thank the HELCOM delegations of Poland, Germany and Russia as well as the HELCOM Secretariat and the Finnish Maritime Administration for their corrections to the manuscript.